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Searches for New Physics at CMS

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Summary. — The first searches for New Physics with the CMS detector at the LHC are presented. The discussed analyses are based on the data sample recorded in 2010 at a centre-of-mass energy of 7 TeV, which corresponds to an integrated luminosity of about $35\,\mathrm{pb}^{-1}$. Searches for excited vector bosons, leptoquarks, extra dimensions as well as for supersymmetry in different final states are presented. No significant deviations from Standard Model expectations have been observed and thus limits on the parameter space of different New Physics scenarios are derived.

PACS 11.30.Pb – Supersymmetry.
PACS 14.80.Sv – Leptoquarks.
PACS 14.70.Pw – Other gauge bosons.

1. – Introduction

The start of operations at the Large Hadron Collider (LHC) at a centre-of-mass energy of 7 TeV in 2010 has marked the beginning of a new era in the search for physics beyond the Standard Model (SM). In 2010, the CMS experiment [1] recorded a data sample with integrated luminosity of about $35\,\mathrm{pb}^{-1}$ of proton-proton collisions. Thanks to the much higher centre-of-mass energy of the collisions, the physics reach is already comparable to or larger than what has been achieved at previous experiments at LEP or the Tevatron. In this article we report the results of the first searches for excited vector bosons, leptoquarks and microscopic black holes. Furthermore, we discuss the results of the first searches for supersymmetry (SUSY) involving missing transverse energy.

2. – W′ and Z′ searches

Several extensions of the SM predict the existence of further gauge bosons that can be regarded as heavy analogues of the SM gauge bosons W and Z. Examples of such models are left-right symmetric models [2-4], compositeness models [5] and Little Higgs models [6].

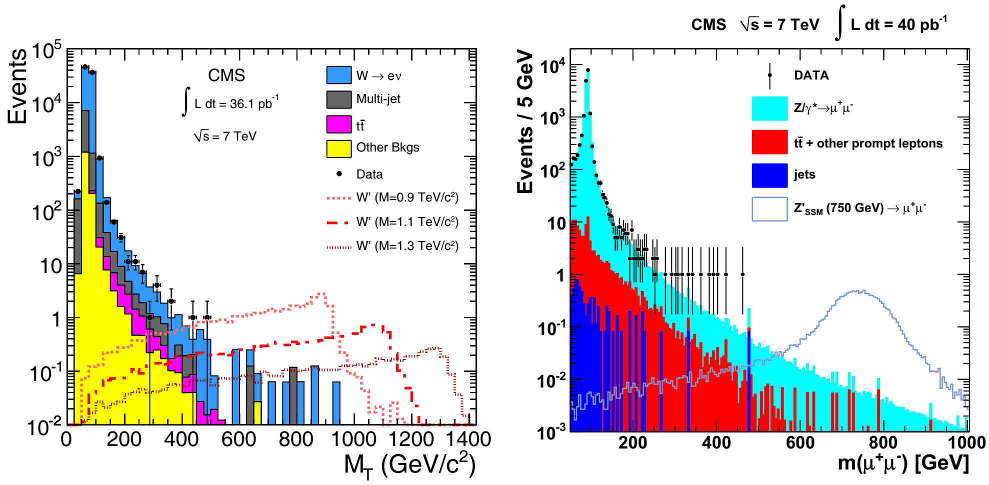

Fig. 1. – Left: transverse mass distributions for selected electron events in the W′ search. Right: invariant mass distributions for dimuon events in the Z′ search.

The search for an excited W boson, W′, is generally explored using a benchmark model [7] where the W′ has the same left-handed fermionic couplings as its SM counterpart and where interactions with the SM gauge bosons are excluded. The most easily identifiable experimental signature thus consists of a high-p_T lepton accompanied by large missing transverse momentum due to the undetected escaping neutrino. The primary discriminating variable is the transverse mass M_T which is the equivalent of the invariant mass of a four-vector computed with only the transverse components of those four-vectors:

$$M_\mathrm{T} = \sqrt{2 \cdot E_\mathrm{T}^\mathrm{lep} \cdot E_\mathrm{T}^\mathrm{miss} \cdot (1 - \cos\Delta\phi(\mathrm{lep}, E_\mathrm{T}^\mathrm{miss}))}\,. \qquad (1)$$

As with a W, the M_T distribution of W′ events is expected to exhibit a characteristic Jacobian edge at the value of the mass of the decaying particle. Events are selected where an electron with transverse momentum, $p_\mathrm{T} > 30\,\mathrm{GeV}$ ($p_\mathrm{T} > 25\,\mathrm{GeV}$ for muons) has been identified. As the signal topology is a two-body decay which reconstructs to a high mass, the energy of the neutrino and electron are expected to be mostly balanced in the transverse plane, both in direction and in magnitude. We therefore require $0.4 < E_\mathrm{T}^\mathrm{lep}/E_\mathrm{T}^\mathrm{miss} < 1.5$. For the same reason, we require that the angle between the electron and the $E_\mathrm{T}^\mathrm{miss}$ be close to π radians: $\Delta\phi(\mathrm{lep}, E_\mathrm{T}^\mathrm{miss}) > 2.5\,\mathrm{rad}$. The main SM backgrounds stems from W→ $\ell\nu$ decays in the tails of the SM W mass distribution. Figure 1 shows the transverse mass distribution for selected events with electrons [8] and the comparison with expected SM backgrounds from Monte Carlo (MC) simulation. In addition, the expected signal from a W′ with different masses is overlaid. In the absence of a signal, limits on the mass and production cross-section times branching fraction are set. This is shown in fig. 2. In electron (muon) channel, a W′ with SM couplings and branching fractions can be excluded at the 95% confidence level (CL) for masses up to 1.36 (1.40) GeV [8, 9]. Combining the results from the two channels results in an exclusion of W′ masses up to 1.58 GeV.

Analogous to the W′ searches, a search for a Z′ signature has been carried out [10]. Here, the high mass part of the Z resonance tail is studied. Events with two oppositely

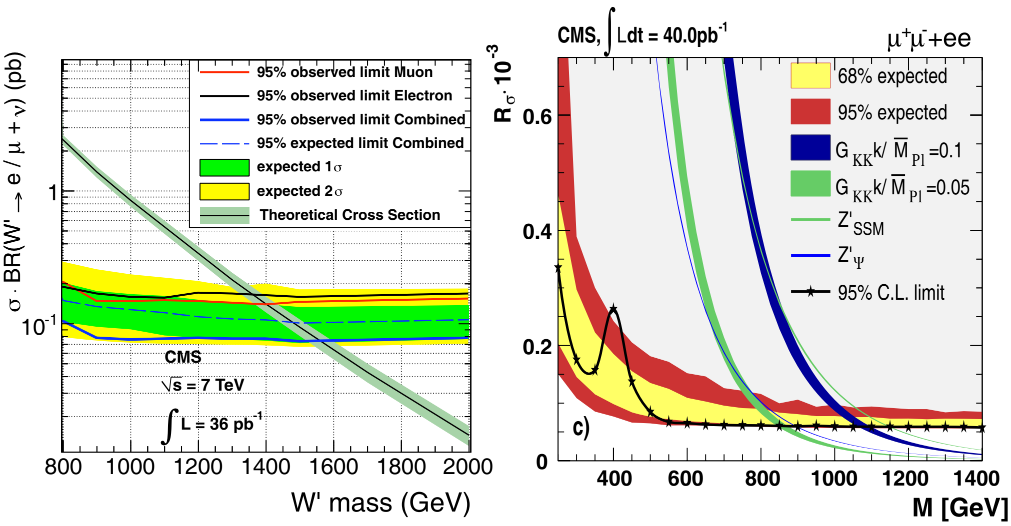

Fig. 2. – Left: upper limits on the production cross section times branching fraction as a function of the W′ mass for the electron channel, the muon channel and the combination of both. Right: upper limits on the production ratio R_σ of cross section times branching fraction into lepton pairs for $\mathrm{Z}'_{\mathrm{SSM}}$ and G_{KK} production and Z'_{Ψ} boson production as a function of resonance mass M.

charged electrons (muons) with $p_\mathrm{T} > 25\,\mathrm{GeV}$ ($p_\mathrm{T} > 20\,\mathrm{GeV}$) are selected. The dilepton invariant mass spectrum for di-muon events is shown in fig. 1, together with the expected SM backgrounds and an expected signal from a Z′ with mass of 750 GeV. In the absence of an excess of events in the high mass tail over the SM expectation, limits on the production cross section of Z′ with respect to SM Z are set as a function of the Z′ mass (see fig. 2). By combining the electron and muon channels, the following 95% CL lower limits on the mass of a Z′ resonance are obtained [10]: 1140 GeV for the $\mathrm{Z}'_{\mathrm{SSM}}$ [11], and 887 GeV for Z'_{Ψ} [11] models. Randall-Sundrum Kaluza-Klein gravitons G_{KK} [12, 13] are excluded below 855 (1079) GeV for values of couplings 0.05 (0.10).

3. – Leptoquark searches

Several extensions of the standard model [14-18] predict the existence of leptoquarks (LQ), hypothetical particles that carry both lepton and baryon numbers and couple to both leptons and quarks. Leptoquarks are fractionally charged and can be either scalar or vector particles. A search for pair-produced first (second) generation leptoquarks is carried out in events with two electrons (muons) and two jets, each with $p_\mathrm{T} > 30\,\mathrm{GeV}$. The main backgrounds from Z decays is rejected by requiring $M_{\mathrm{ee}} > 125\,\mathrm{GeV}$ ($M_{\mu\mu} > 115\,\mathrm{GeV}$). After this preselection, the main discriminating variable is defined as the scalar sum of the lepton and jet p_T's: $S_\mathrm{T} = E_\mathrm{T}(\ell_1) + E_\mathrm{T}(\ell_2) + E_\mathrm{T}(\mathrm{jet}_1) + E_\mathrm{T}(\mathrm{jet}_2)$. The two variables are shown for di-electron events in fig. 3 [19] where good agreement between data and SM expectation is found.

Figure 4 [19, 20] shows the 95% CL upper limit on the LQ pair production cross section times β^2, where β is the branching fraction for $\mathrm{LQ} \to qe(\mu)$([1]), as a function

([1]) (1-β) is the branching fraction for $\mathrm{LQ} \to q\nu_e(\nu_\mu)$.

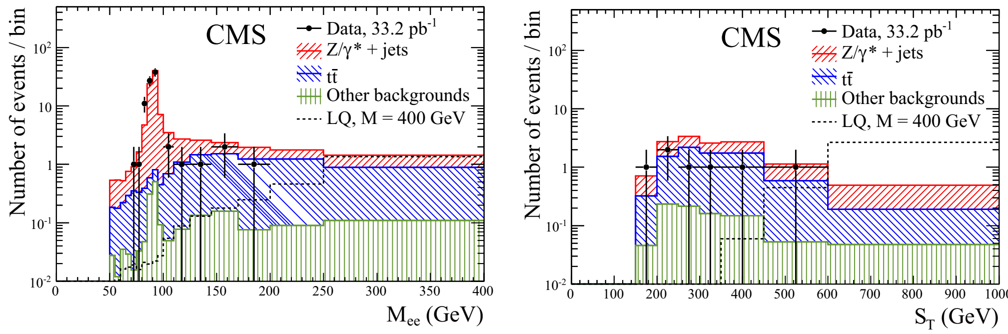

Fig. 3. – Invariant mass distributions for dielectron events after preselection (left) and the S_{T} distribution after final selection (right).

of the LQ mass. First (second) generation leptoquarks can be excluded at 95% CL for masses up to 384 GeV (394 GeV) for $\beta = 1$ [19, 20].

4. – Searches for microscopic black holes

Extensions to the Standard Model proposing the existence of extra spatial dimensions and low-scale quantum gravity offer the possibility of copious production of microscopic black holes [21, 22]. In this model, the true Planck scale in $4 + n$ dimensions, M_D, is consequently lowered to the electroweak scale, much smaller than the apparent Planck scale of $M_{\mathrm{Pl}} \sim 10^{16}$ TeV seen by a 3+1 spacetime observer. The relationship between M_D and M_{Pl} follows from Gauss's law and is given as $M_{\mathrm{Pl}}^2 = 8\pi M_D^{n+2} r^n$.

The creation of microscopic black holes is possible when the two partons from colliding beams pass each other at a distance smaller than the Schwarzschild radius corresponding to their invariant mass. The such produced black holes would decay instantly via Hawking

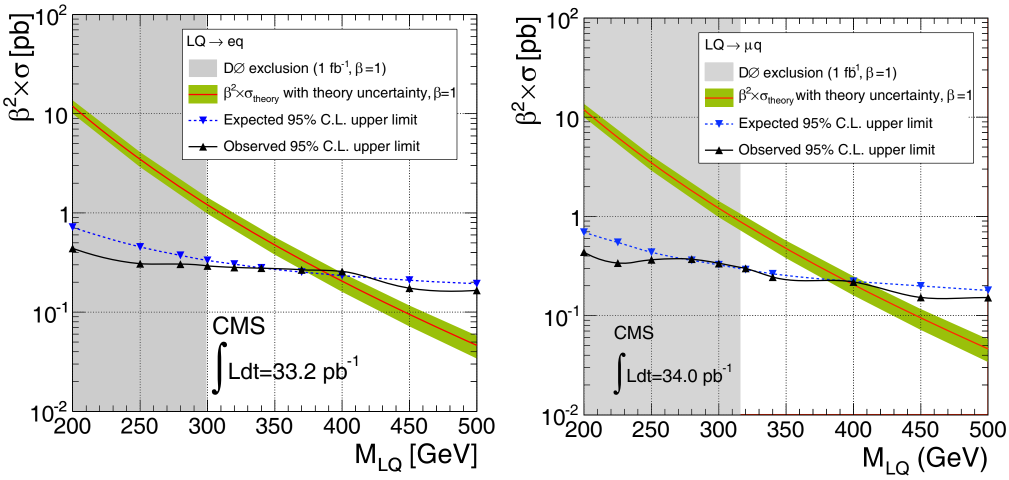

Fig. 4. – Upper limits on the production cross section times branching fraction for first generation leptoquarks (left) and second generation leptoquarks (right).

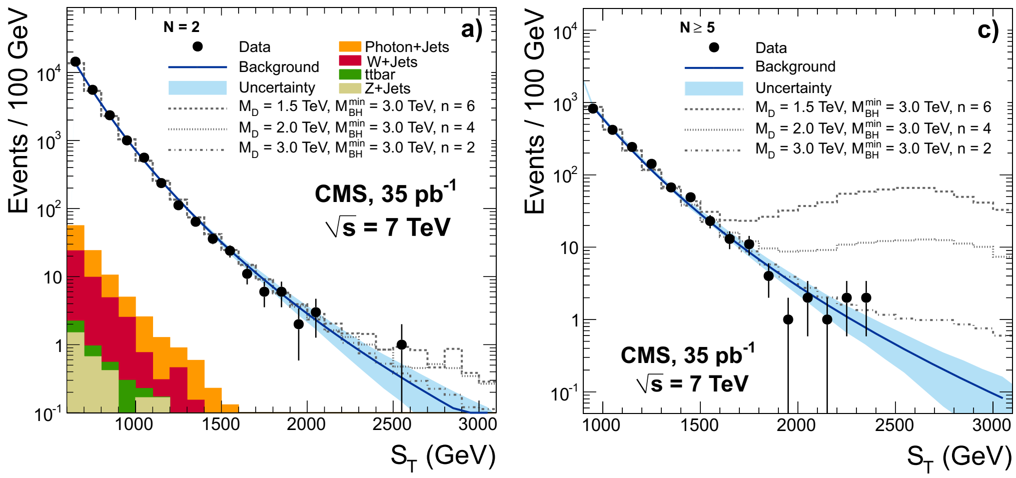

Fig. 5. – The S_{T} for events with object multiplicity of two (left) and ≥ 5 (right). A possible signal contribution from black hole models with different effective Plack scale M_D and number of extra dimensions n is overlaid.

evaporation with an emission of a large numbers of energetic objects. The search thus uses the scalar sum of all measured physics objects i (jets, muons, electrons, photons, and the missing energy) with transverse energy, $E_{\mathrm{T}} > 50\,\mathrm{GeV}$ as discriminating variable: $S_{\mathrm{T}} = \sum_{i=1}^{n} E_{\mathrm{T}}^{i}$.

The main standard model background consists of QCD multi-jet production but it was found that the shape of the S_{T} distribution does not depend on the object multiplicity. It is thus possible to obtain a purely data driven background estimation for this search, as the S_{T} shape can be obtained from QCD di-jet events. Due to the small object multiplicity, this sample is basically signal free. The S_{T} distribution for object multiplicities of two and ≥ 5 is shown in fig. 5 [23]. No excess of events at high S_{T} over the SM expectation is observed. In fig. 6 the 95% CL upper limits in the black hole production cross section are shown for different values of the effective Planck scale M_D and the number of extra spatial dimensions n. Furthermore, the 95% CL limits on the black hole mass as a function of M_D are shown [23]. The lower limits on the black hole mass at 95% CL range from 3.5 to 4.5 TeV for values of the effective Planck scale up to 3 TeV.

5. – Searches for Supersymmetry

Supersymmetry is one of the most promising extensions to the Standard Model as it provides solutions to several shortcomings of the former. SUSY provides a solution to the hierarchy problem by stabilizing the Higgs mass through the introduction of new particles. In addition, it naturally leads to a unification of the strong and electroweak interactions at a scale around 10^{16} GeV and it predicts electroweak symmetry breaking, which is the basis for understanding all masses via the Higgs mechanism. Finally, it can accommodate a weakly interacting massive stable particle that can serve as a dark matter candidate, thus providing a solution to one of the most intriguing problems in modern particle physics and cosmology. In the following, searches for SUSY based on different event topologies are discussed.

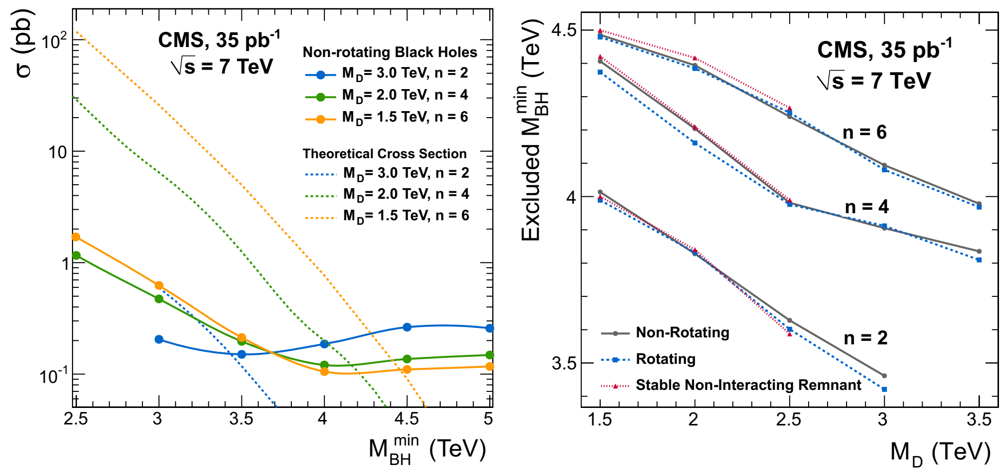

Fig. 6. – Left: the 95% CL upper limits on the black hole production cross section (solid lines) and three theoretical predictions for the cross section (dashed lines), as a function of the black hole mass. Right: the 95% CL limits on the black hole mass as a function of the multidimensional Planck scale M_D for several benchmark scenarios. The area below each curve is excluded by this search.

5˙1. *The jets + missing energy topology.* – The dominant production channels of heavy coloured sparticles at the LHC are squark squark, squark gluino and gluino gluino pair production. In the context of SUSY with R-parity conservation, heavy squarks and gluinos decay into quarks, gluons and other SM particles, as well as a neutralino, *i.e.* the lightest supersymmetric particle (LSP), which escapes undetected, leading to final states with several hadronic jets and large missing transverse energy. While squark squark production usually leads to two jets, gluino production typically results in higher jet multiplicities.

For the jets + missing energy topology the background from multijet production, as predicted by quantum chromodynamics (QCD), is several orders of magnitude larger than the typical signal expected from SUSY. For this type of events, missing transverse energy is introduced through mis-measurements of jets in the detector. For this reason, a kinematic variable, α_{T}, defined for di-jet events as

$$\alpha_{\mathrm{T}} = \frac{E_{\mathrm{T}}^{\mathrm{jet}_2}}{M_{\mathrm{T}}} = \frac{\sqrt{E_{\mathrm{T}}^{\mathrm{jet}_2}/E_{\mathrm{T}}^{\mathrm{jet}_1}}}{\sqrt{2(1-\cos\Delta\phi(\mathrm{jet}_1,\mathrm{jet}_2))}}\,, \tag{2}$$

is employed to separate events with real missing energy from those where missing energy is introduced through mis-measurements. For QCD di-jet events, where the jets are expected to be balanced in p_{T} and back-to-back in azimuthal angle ϕ, this variable has an expectation value of 0.5, and < 0.5 in case the two jets are not p_{T} balanced, thus exploiting the scalar and angular information of the measured jets. For events with real missing energy, such as SUSY signal but also $\mathrm{t\bar{t}}$, $\mathrm{W}\to \ell\nu$, and $\mathrm{Z}\to \nu\nu$ + jets events with small transverse mass, α_{T} can take on values > 0.5. Multi-jet events are reduced to a di-jet topology by constructing pseudo-jets and using these in the calculation of α_{T}. In the calculation of α_{T} jets with $E_{\mathrm{T}} > 50\,\mathrm{GeV}$ are considered and $H_{\mathrm{T}} = \sum_{i=1}^{n} E_{\mathrm{T}}^{\mathrm{jet_i}} > 350\,\mathrm{GeV}$

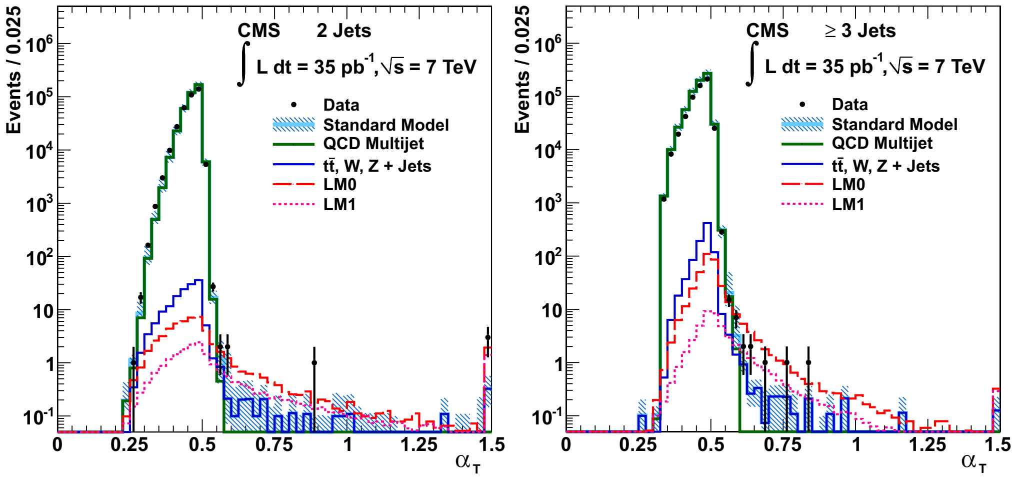

Fig. 7. – α_T distribution for dijet events (left) and events with ≥ 3 jets (right).

is required. Figure 7 shows the α_T distribution for events with two (left) and ≥ 3 jets (right) where the strong rejection power against QCD multi-jets events can be seen. The remaining backgrounds from $t\bar{t}$ and W$\rightarrow \ell\nu$ decays are estimated with an inclusive muon data control sample whereas the background from Z$\rightarrow \nu\nu$ + jets events is estimated from a photon + jets control sample. The combined background prediction amounts to $10.5^{+3.6}_{-2.5}$(stat) $\pm$ 2.5(syst) events compared to 13 events found in data [24]. We use this result to set limits on the parameter space of the constrained minimal supersymmetric extension of the standard model (CMSSM). This is shown in fig. 8 [24] which shows the m_0 *vs.* $m_{1/2}$ plane, *i.e.* the universal scalar and gaugino mass, respectively. It can be seen that the exclusion exceeds by far the limits set previously by experiments at LEP and the Tevatron.

5˙2. *The opposite charge dilepton channel.* – Pair produced heavy particles such as squarks and gluinos can undergo cascade decays to SM particles, thus producing leptons

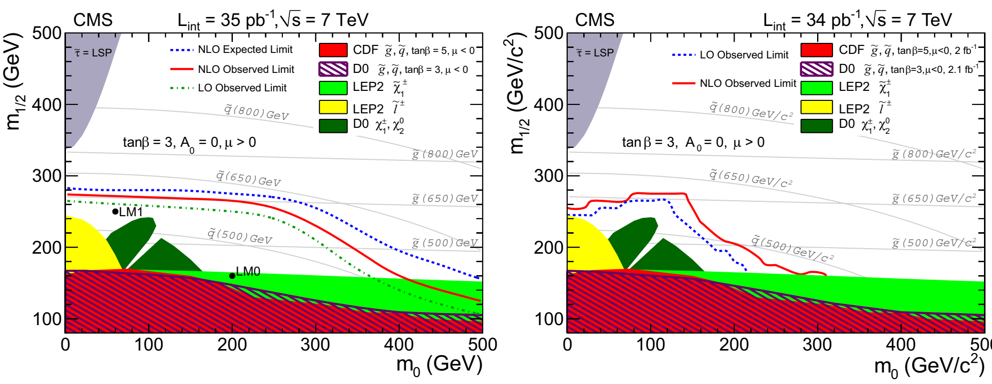

Fig. 8. – 95% CL exclusion in the m_0 *vs.* $m_{1/2}$ plane of the CMSSM. Left: jets + missing transverse energy analysis based on α_T. Right: opposite charge dilepton analysis. The areas below the solid lines are excluded.

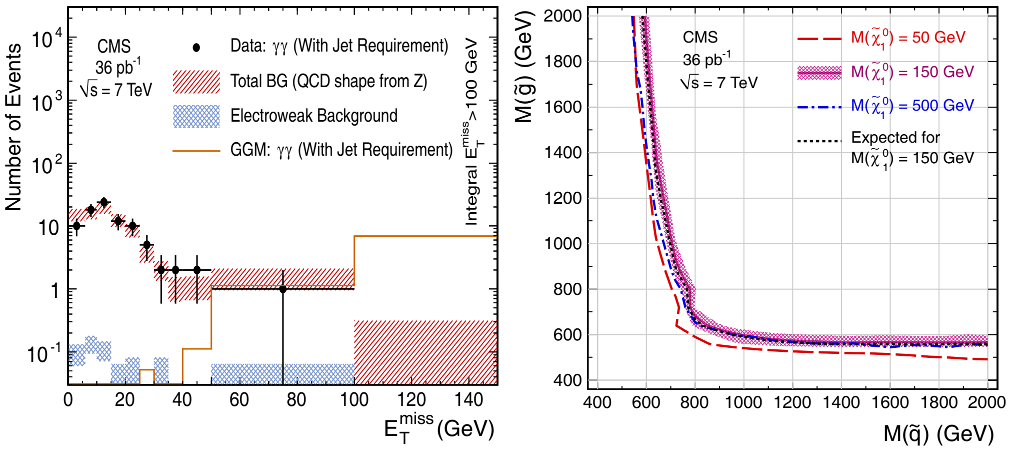

Fig. 9. – Left: missing energy $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution for di-photon events and data driven background estimation. Right: lower 95% CL exclusion limits on the squark and gluino masses in the GGM benchmark model for 50, 150, and 500 GeV neutralino masses. The areas below and to the left of the lines are excluded.

in addition to hadronic jets. The requirement of isolated leptons significantly reduces the background from QCD multi-jet events. Requiring two oppositely charged leptons basically only leaves $\mathrm{t\bar{t}}$ events as SM background. Events are selected requiring at least one isolated lepton with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and the other with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$. In addition, at least two jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ that are well separated from the leptons are required and the scalar sum of their transverse energies is required to exceed $H_{\mathrm{T}} > 300\,\mathrm{GeV}$. Furthermore, the missing transverse energy is $E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$ is required and $y = E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} > 8.5\sqrt{\mathrm{GeV}}$, which leaves about 1% of the di-lepton $\mathrm{t\bar{t}}$ events. To determine the remaining backgrounds, the fact that H_{T} and y are nearly uncorrelated is exploited. Defining signal and background regions in both variables, the expected number of background events in the joint signal region can be obtained from the three control regions [25]. A second method exploits the idea that in di-lepton $\mathrm{t\bar{t}}$ events the p_{T} distributions of the charged leptons and neutrinos from W decays are related, because of the common boosts from the top and W decays. This relation is governed by the polarization of the W's, which is well understood in top decays in the SM and can therefore be reliably accounted for. The observed $p_{\mathrm{T}}(\ell\ell)$ distribution is then used to model the $p_{\mathrm{T}}(\nu\nu)$ distribution, which is identied with $E_{\mathrm{T}}^{\mathrm{miss}}$.

In the signal region with $y = E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} > 8.5\sqrt{\mathrm{GeV}}$, one event is observed in data compared with a background expectation of 1.3 ± 0.8 (stat) ± 0.3 (syst) from the first background estimation method and 2.1 ± 2.1 (stat) ± 0.6 (syst) events from the second method. Using the error weighted average of the two background predictions of 1.4 ± 0.8 [25], a 95% CL exclusion limit in the m_0 *vs.* $m_{1/2}$ plane of the CMSSM is calculated and displayed in fig. 8 [25].

5˙3. *The diphoton channel.* – Supersymmetric models with general gauge mediation (GGM) [26,27] have the gravitino as the lightest supersymmetric particle. In the models considered here, the next-to-lightest supersymmetric particle is the lightest neutralino that is assumed to decay promptly to an escaping gravitino and a photon. The search requires two isolated photons with $E_{\mathrm{T}} > 30\,\mathrm{GeV}$ in the barrel of the electromagnetic calorimeter and at least one jet with $E_T > 30$ GeV. The main backgrounds arise from SM processes with misidentified photons and/or mismeasured E_T^{miss}. The dominant contribution comes from mismeasurement of E_T^{miss} in QCD processes such as direct diphoton, photon plus jets, and multijet production, with jets mimicking photons in the latter two cases. The E_T^{miss} distribution for $\gamma\gamma$ events is shown in fig. 9 [28]. For $E_T^{miss} > 50$ GeV, one event is observed in data with a SM background expectation of 1.2 ± 0.4 (stat) ± 0.8 (syst) events. The background expectation is obtained from two different data-driven background estimation methods, selecting two fake photons in a QCD multi-jet sample and two electrons from $Z \rightarrow e^+e^-$ decays, respectively [28]. In the absence of a signal, the observed event yield is used to set limits on the production cross section of GGM models as a function of the squark and gluino mass. The observed 95% confidence level (CL) cross section limits vary between 0.3 and 1.1 pb for squark and gluino masses between 500 and 2000 GeV and a neutralino mass of 150 GeV. These cross section limits can then be turned into lower limits on the squark and gluino masses which are displayed in fig. 9 [28] for different neutralino masses.

6. – Summary

Based on the data collected in 2010, the CMS collaboration has carried out a wide variety of searches for physics beyond the Standard Model. Unfortunately, so far no evidence for a deviation from the SM expectation has been found but the sensitivity of almost all these searches exceeds those of previous experiments at LEP and the Tevatron. In the presented analyses great effort was made to determine the remaining Standard Model backgrounds from data control samples with only small reliance on the Monte Carlo simulation of the involved processes. This bodes well for future searches on the much larger data sample that will be collected in 2011 and 2012.

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